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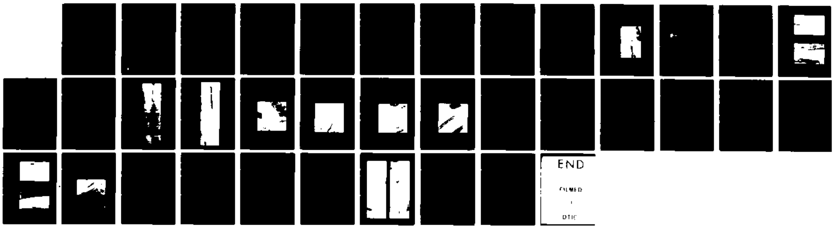

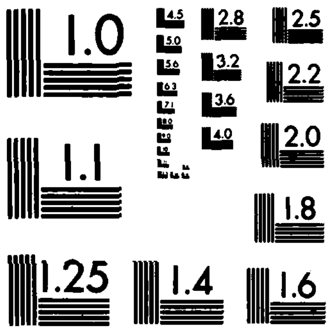

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RESUSPENSION OF BED MATERIAL AND WAVE EFFECTS

ON THE

ILLINOIS AND UPPER MISSISSIPPI RIVERS

CAUSED BY BOAT TRAFFIC

Prepared for

U. S. Army Engineer District
St. Louis
Contract No. LMSSD 75-881

by

S. Karaki
and
J. vanHoften

Engineering Research Center
Colorado State University
Fort Collins, Colorado

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The purpose of this study is to analyze, qualitatively, the effects of waterborne traffic on the Illinois and Upper Mississippi Rivers with regard to the resuspension of bed sediments caused by boat passage and to estimate the increase in turbidity due to an increase in river traffic. The generation of turbulence by tow boats and other surface crafts is ~~also discussed~~ in this report. The generation of waves by boats with consequent erosion of the banks is also discussed. Aerial color infrared photographs and published information were discussed to aid the analysis.

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1.0 OBJECTIVE

The purpose of this study is to analyze, qualitatively, the effects of waterborne traffic on the Illinois and Upper Mississippi rivers with regard to the resuspension of bed sediments caused by boat passage and to estimate the increase in turbudity due to an increase in river traffic. The generation of turbulence by tow boats and other surface crafts is also discussed in this report. The generation of waves by boats with consequent erosion of the banks is also discussed. Aerial color infrared photographs and published information were used to aid the analysis.

2.0 BACKGROUND

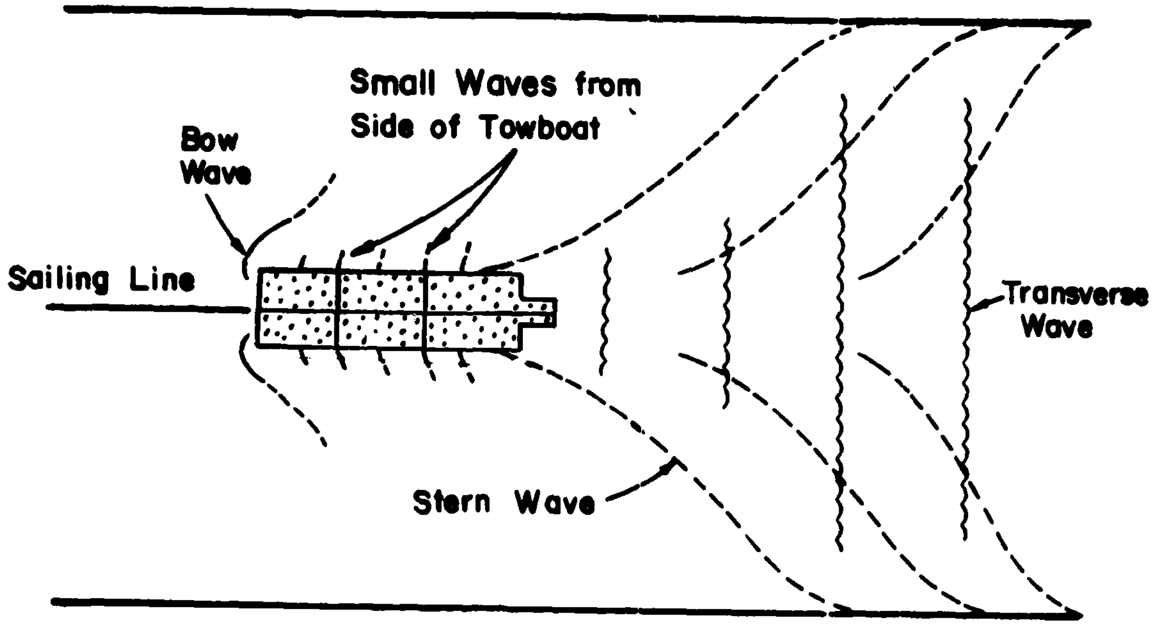
2.1 River Reach Studied

The river system under study consisted of the Upper Mississippi River from Locks and Dam No. 26 at Alton, Illinois, near St. Louis, Missouri, upstream to St. Paul, Minnesota; and the Illinois River from its confluence with the Mississippi River upstream to Chicago, Illinois. There are significant differences between the two rivers in bed material grain sizes and widths of the rivers. In general, the Mississippi River has a sand bed with mean size, d_{50}, of about 0.25 mm, and a wide channel, whereas the Illinois River has a bed composed of silts and clays and a narrow channel. Both rivers have a series of locks and dams for traffic and river flow control with a minimum depth of 9 feet in the navigation channels. The major emphasis of this study concerns the Illinois River which is more likely to be affected by an increase in traffic because of its smaller size and finer bed material.

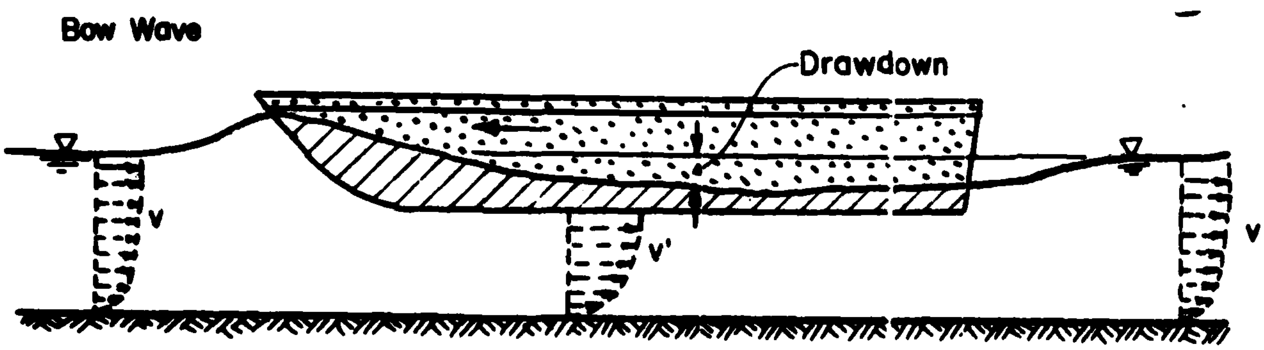
2.2 Description of Typical Boat Passage

Waterborne traffic can be divided into two broad categories; large slow towboats, and smaller faster pleasure crafts. The towboats range from single 35- by 195-foot units to long trains 3 units wide by 6 units long. Within this report, a towboat is defined as a unit consisting of barges and a tugboat which controls and powers the barges. Present lock size limits towboats to 9 barges in a lock at one time. Fully loaded, the barges have a draft of 9 feet.

The effect of a moving towboat on the river is described below. As seen from above the water surface, a pattern of waves is developed as shown approximately in Figure 1a. Bow waves are generated at the front of the towboat. Smaller waves are generated at the sides, and at the trailing end, stern waves are generated which are led by a trough, followed by a crest. These waves diverge from the sailing line. There are also waves in the wake of the towboat which are transverse to the sailing line and are contained in the region of the stern waves. The amplitudes of the waves are primarily dependent on the boat velocity. Beneath the surface, a complex turbulent flow pattern is generated. (There is an increase in velocity of water beneath the boat relative to the mean velocity in the river.) The acceleration of flow depends on the proximity of the bottom of the barge to the river bed and is due to pressure differences created by the water surface profile along the sides of the barge as shown in Figure 1b. Additionally, velocities accelerate around the sides of the barges. The interaction of the two flow patterns create a region of marked turbulence and increased velocities along the sides. The propellers of the tug also add turbulence to the already



a. Waves Generated by a Towboat



b. Water Surface Profile Along the
Side of the Boat

Figure 1. Surface Disturbances Created by Boats.

disturbed flow caused by the barges. Depending on the proximity of the boat to the streambed and the sizes of bed material, a certain amount of bed sediment is either moved on the bed or suspended in the flow. The material in suspension will remain until the turbulence decays sufficiently for the material to settle out. An example of the plume of sediment created by a towboat is shown in the infrared photograph of Figure 2. Note also the evidence of suspended sediment along the side of the towboat at the bottom right of the photograph.

3.0 ANALYSIS OF RESUSPENSION

3.1 Flow Description in the Vicinity of a Typical Towboat

The series of flow patterns shown in Figure 3 illustrates the effects of the proximity of the keel to the river bottom. With either a shallow draft or deep channel, as shown in Case 1, even though turbulence is generated around the towboats, the effect of disturbances on the riverbed is small. With deeper draft and less clearance between the keel and riverbed, which is the more normal situation with towboats on the river, a flow pattern with large separation region at the sides and accelerated flow beneath the boat results, as seen in Case 2. The extreme example of Case 3 occurs when the keel is almost on the riverbed. In this case, there is little flow under the boat; nearly all of the water displaced by the boat is deflected and accelerated to the sides, forming a pattern similar to flow around a fixed obstacle in a river, such as a bridge pier. An increase in boat speed increases relative magnitudes of local velocities and intensities of turbulence in the separation region. The basic flow patterns remain the same.

Direction of Flow →

Figure 2. Sediment Resuspended by a Typical Towboat on the Illinois River.

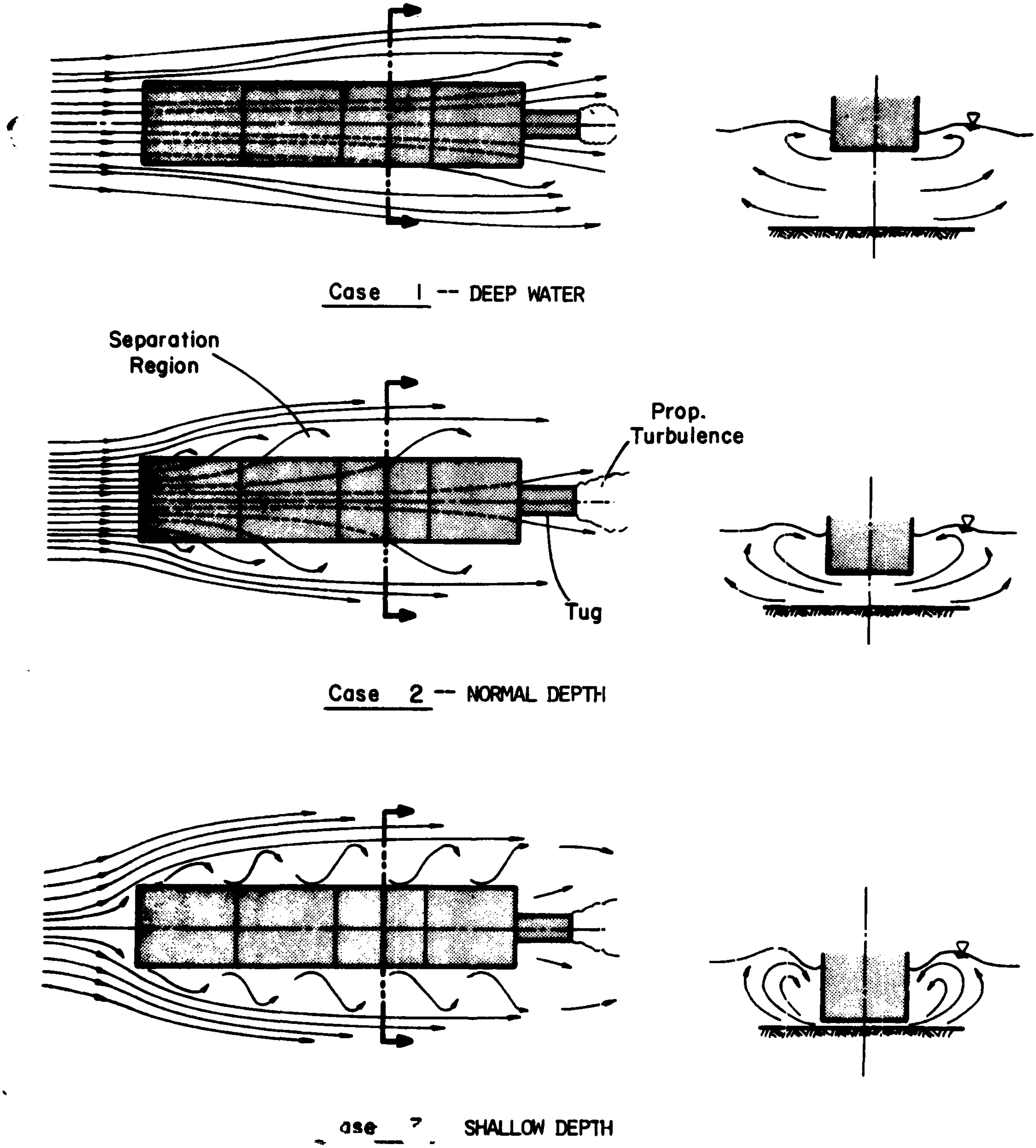


Figure 3. Acceleration of Flow and Turbulence Created by Towboats.

3.2 Tugboat Effects

Due to the small size of the tugboat in relation to the barges the principal effect of the tugboat is to add turbulence, generated by the propellers, to the disturbed flow behind the barges. Figures 4 and 5 are presented to illustrate disturbances created by nearly stationary tugs and slow moving tugs respectively. The stationary tug, maneuvering a barge into a lock or along a bank, creates a turbulent wash from the props that spreads downward to the streambed and erodes the bed in the form of a scour hole (Felkel 1973). As the towboat accelerates, the effect of the prop wash, in relation to the turbulence caused by the barges, diminshes. In effect, the propellers add small-scale turbulence to a highly disturbed flow field containing large scale turbulence and eddies. The prop-wash from the tugs is always present behind a moving towboat and an examination of infrared photographs indicates that with a moving towboat, the large scale disturbance created by the towboat persists while the small scale turbulent prop-wash is not evident beyond a short distance behind the towboat.

3.3 Small Boat Effects

Small, fast moving pleasure craft with a shallow draft, do not disturb the flow sufficiently to cause significant resuspension of the bed material. The effects are similar to that depicted in Case 1 of Figure 3. The main effect of small boats is to generate surface waves which propagate to the shore. These wave effects are discussed in Section 4.

Direction
of Flow

Figure 4. Tug Maneuvering Barges into the LaGrange Lock on the Illinois River.

Direction
of Flow

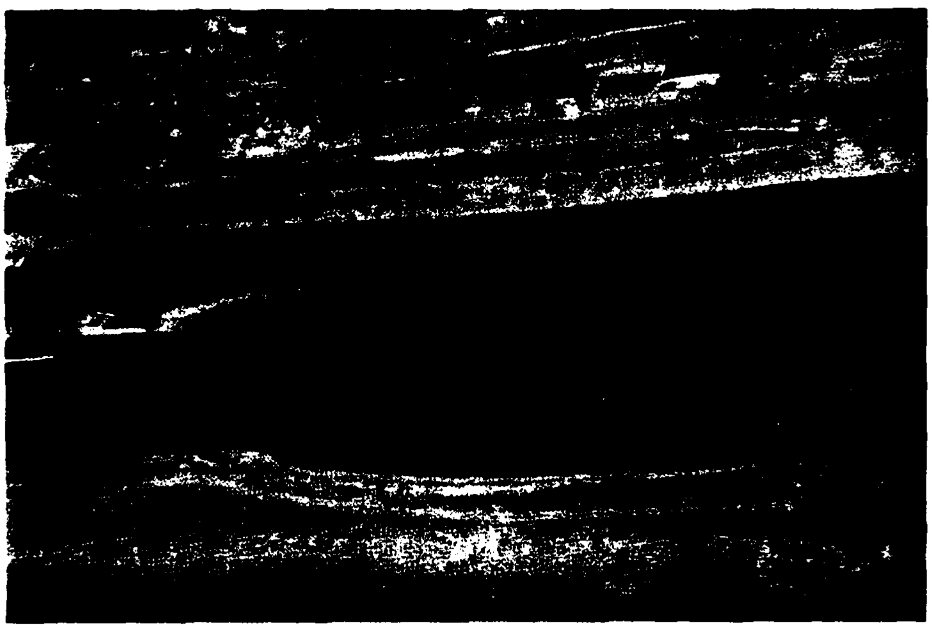


Figure 5. Slow Moving Tug Illustrating Prop Wash. (Illinois River near LaSalle, Illinois.)

3.4 Resuspension of Bed Material

Sediment transport in an alluvial river consists of bed load, and suspended load (Leliavsky, 1966; Lèopold, Wolman and Miller, 1964). Bed load is material that is pushed, rolled or bounced along the river bottom, and suspended sediment load is the fine material carried in suspension above the streambed. The amount or concentration of suspended sediment depends on sediment size, particle fall velocity, river velocity, intensity or turbulence, and amount of fine material introduced upstream into the river.

As discussed earlier, the bed of the Upper Mississippi River is primarily sand while that of the Illinois River consists of finer silts and clays. Basically this difference in bed material of the two rivers is due to the different stream velocities, local geology (soil type), and land use in the watersheds. The quantity of suspended sediment in a river will determine its clarity or turbidity. Due to seasonal variations, the quantity of fine materials in the river changes throughout the year. Generally, rivers are more turbid at high stages due to increased flow and input of sediment, greater ability to transport the fines and scouring of materials that settled during low flow periods. Rivers will tend to be more turbid along the lower reaches than the upper sections because of the accumulation of fines transported downstream.

The very fine-sized suspended sediments (washload) in a stream contribute to the background turbidity level. Any disturbance in the streambed either through increased velocity, or turbulence generated by boat passage suspends material that previously settled. The turbulence that is generated by a boat gradually decays and the resuspended material settles. The time required for settling of suspended material depends on the fall velocity of the particles.

Figures 6 and 7 are representative color infrared photographs of the effect of towboats on the Illinois River. The lighter, blue-grey areas along the sides and behind the boats are regions where the concentration of suspended sediment is greater than in the surrounding water. Figure 8 is a representative photograph of the effect of a towboat on Lake Peoria and Figures 9 and 10 show towboats on the Upper Mississippi River. The photographs show a definite sediment plume trailing behind each towboat for some distance. The large scale turbulence behind the towboats persist as patterns of vertical axis vorticies, a particular example which is shown in Figure 11.

It must be noted that the colors on the infrared photographs only indicate relative concentrations of surface sediment. There is, in general, a concentration profile below the surface such that concentration generally increases with depth. Turbulence in the flow mixes the sediment and water so that the concentration tends to be uniform with depth. Turbulence near the river bed resuspends bed sediments and increases the suspended sediment concentration.

3.5 Effect of Increased Traffic on Resuspension

Measurements of turbidity made by Starret (1971), in the Alton Pool of the Lower Illinois River indicated a background turbidity of 108 Jackson Turbidity Units (JTU) before towboat passage, which increased to 320 units, 6 minutes after passage, and decreased to 240 units, 16 minutes later. To estimate the effects of increased boat traffic past a given point in the river, assume a turbidity relationship with time (at a point on the river) as shown in Figure 12a. If two towboats are traveling in the same direction, the turbidity in the river (at a stationary point) could vary with time as shown in Figure 12b.

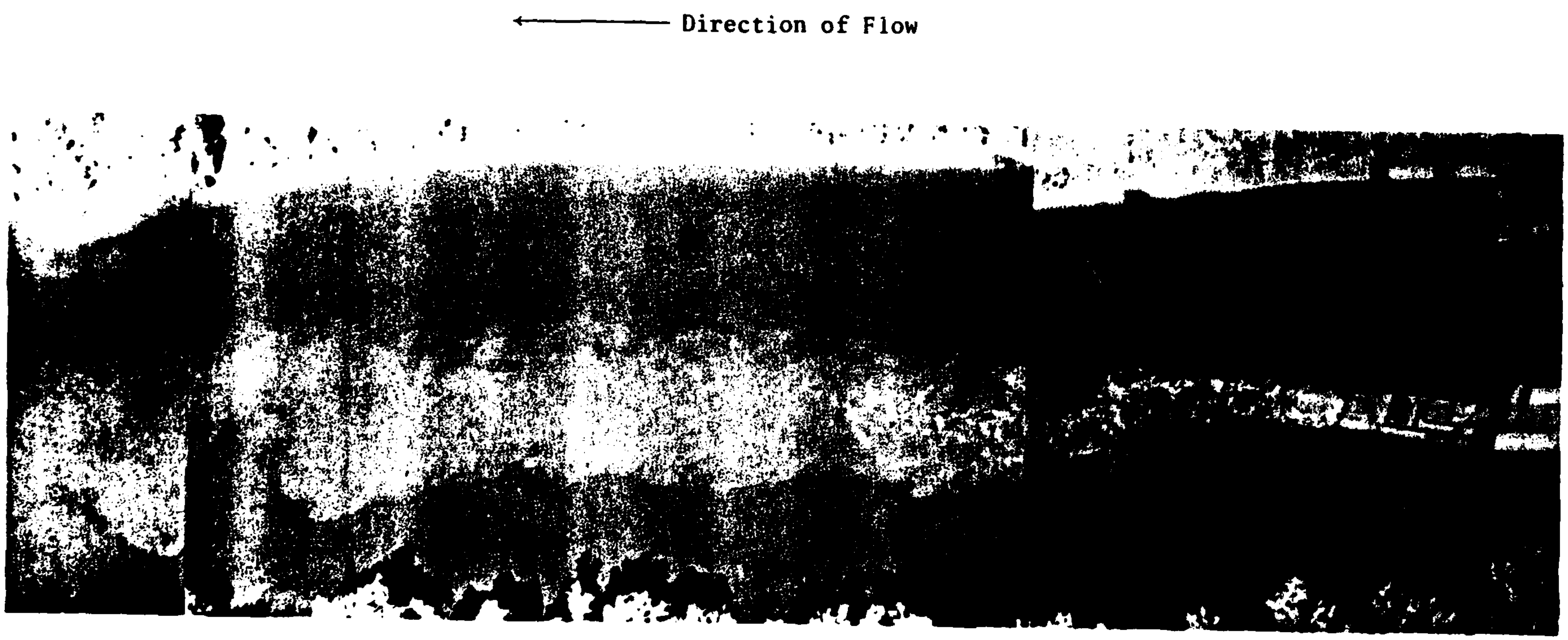


Figure 6. Towboat on the Illinois River near Beardstown, Illinois. (Average Depth along Sailing Line is 16 feet.)

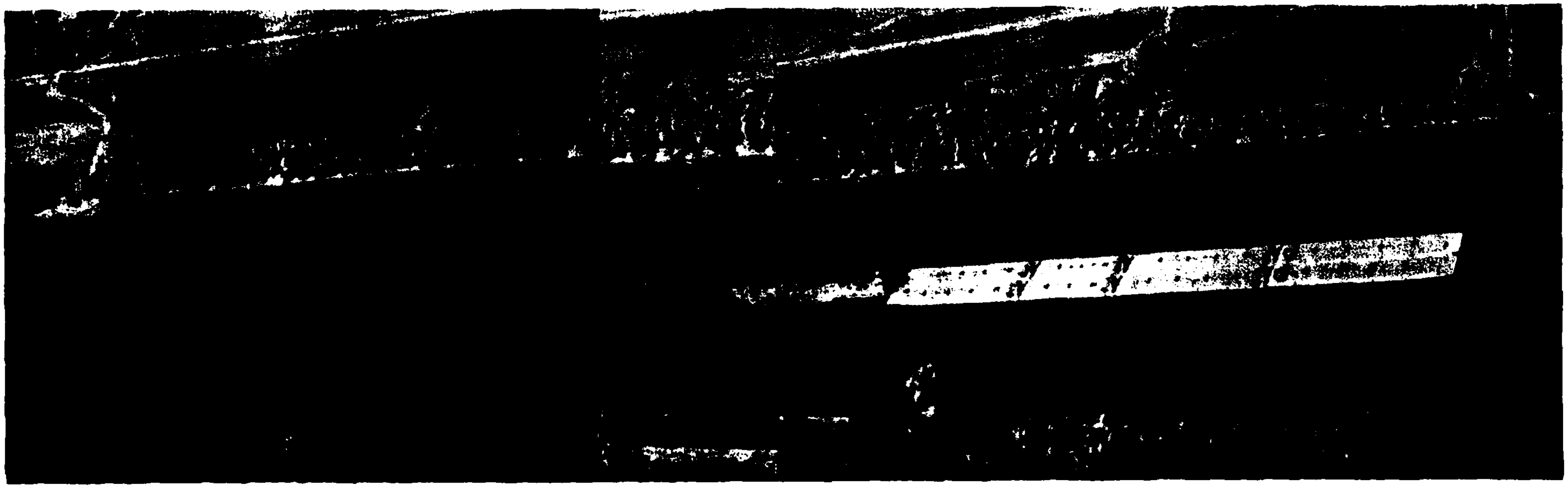


Figure 7. Towboat on the Illinois River near Pearl, Illinois. (Average Depth along Sailing Line is 13 feet.)

Figure 8. Towboat on Lake Peoria.

Direction
of Flow

Figure 9. Towboat on Upper Mississippi River, near Nauvoo, Illinois.

Direction
of Flow

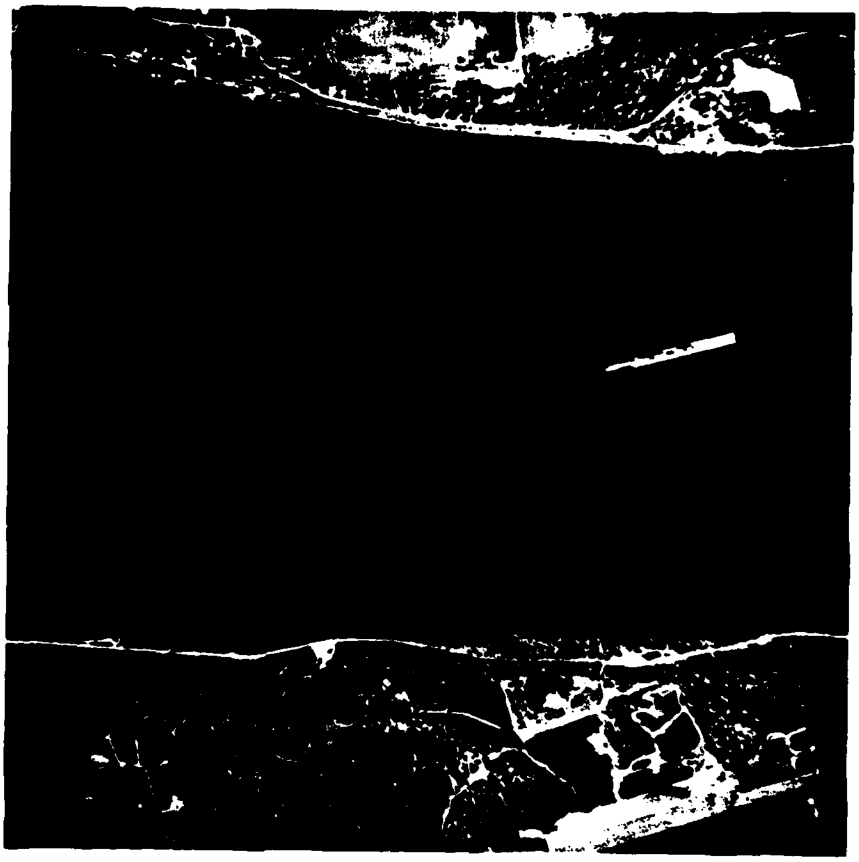


Figure 10. Towboat on Upper Mississippi River, near New Boston, Illinois.

Direction of Flow

Figure 11. Typical Vertical Axis Vortices in the Wake of a Towboat.

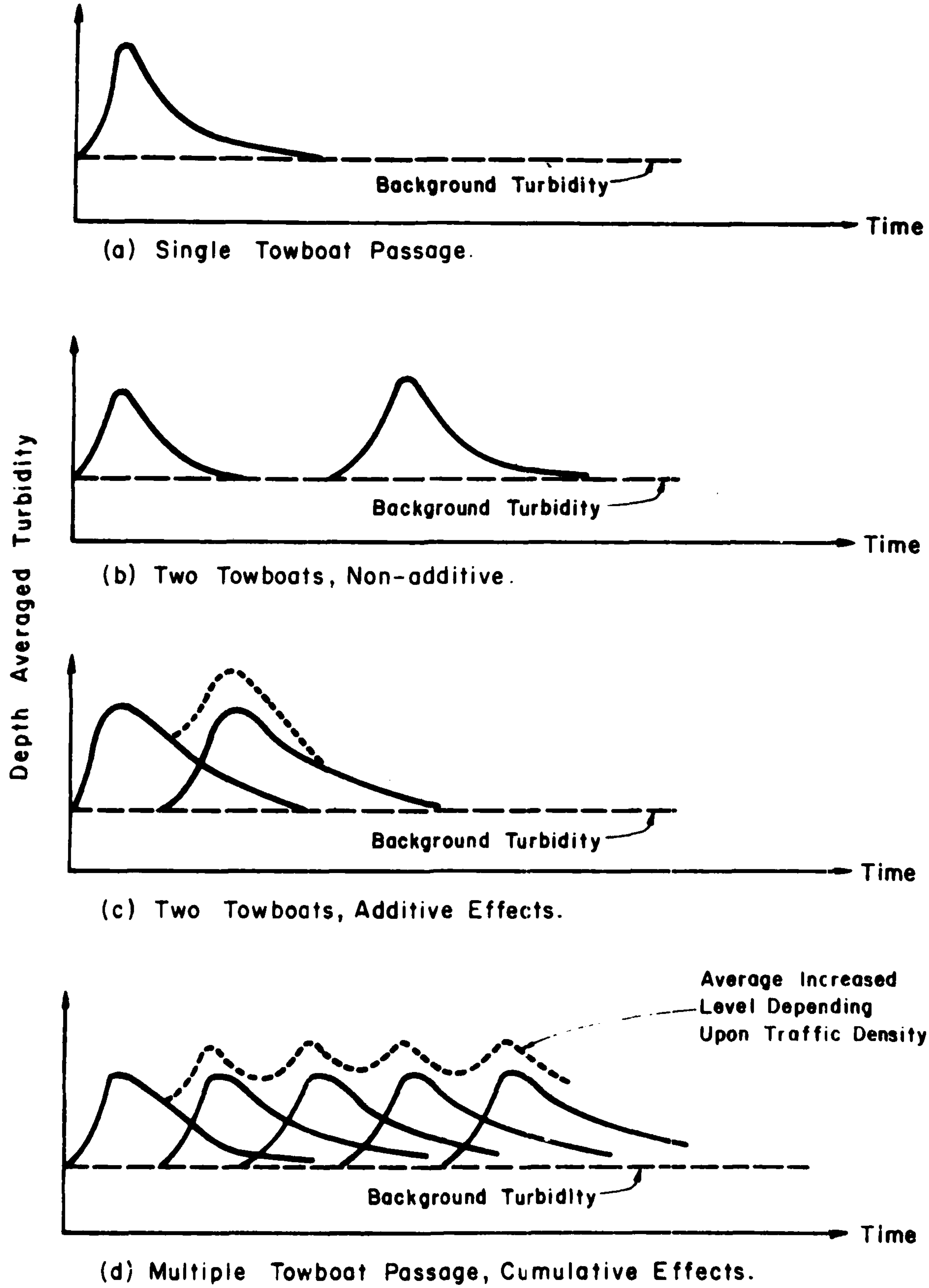


Figure 12. Turbidity Increase Caused by Towboats.

For simplicity, each towboat is assumed to have an equal effect on the river. Because the lag time between towboats is greater than the settling time of the resuspended sediments, there is no significant increase in turbidity in the river by two towboats, which are spaced far apart, as compared to the turbidity created by a single towboat. When the space between towboats is shorter, or equivalently the time period between towboat passage is shorter than the settling time for the resuspended sediments, the turbidity created by the second towboat adds to that of the first. The combined effect is shown as a dashed line in Figure 12c. In this representation, the amount of sediment resuspended by each towboat is assumed to be the same.

The application of this turbidity model to a sequence of towboats, is shown in Figure 12d. It should be noted that there are three times as many towboats passing the fixed point in Figure 12d as in Figure 12b. The combined effect of the increased numbers of towboats (in the same direction) is to increase the turbidity in the river by about 1.5 times the turbidity increase caused by a single towboat in this illustration. Obviously, if the frequency of towboats on the river increases, the combined turbidity increase will be greater than that illustrated in Figure 12d. The utility of this model for estimating turbidity increases at points in the river is that various frequencies of towboats, various sizes and different amounts of turbidity generated by different towboats can be combined to yield an estimate of the increase in level of turbidity on the river. Quantitative data are needed from field measurements to develop turbidity models for towboats of different sizes moving in upstream and downstream directions at different velocities in order to obtain quantitative estimates of the effects of increased river traffic on turbidity. From this analysis, it is clear that the effect of increase in towboat traffic on the river is to increase the turbidity level in the navigation channel. The turbidity level will also increase with a decrease in channel depth and bed material sizes due to the increased local accelerations, turbulence, and ease of resuspension.

3.6 Diffusion Into Backwater Areas

The Upper Mississippi and Illinois Rivers have complex networks of channels, pools, and backwater areas. Water is generally supplied to the backwater areas (sloughs and lakes) through rainfall, and during high river stages, spillage occurs from the main channel (generally the navigation channel) to the backwater areas. Wang and Brabec (1969), studied turbidity in Peoria Lake on the Illinois River and concluded that during periods of high flow, the channel was more turbid than the backwater areas. They also concluded that during low flows the backwater areas were more turbid. The majority of sediment in backwater areas is transported there during high river stages when the naturally suspended load in the channel is high and there is overflow from the main channel. If turbidity is added to the river by increased boat traffic, the transport of suspended material from the main channel to the backwater areas will correspondingly be greater. At normal flows very little if any material is transported to the backwater areas from the main channel. Thus, during normal periods, increase in turbidity due to increased river traffic would be confined to the navigation channel. The sediment plume from towboats, shown in the infrared photographs, spreads across the main channel but the suspended fine material can be carried to backwater areas only if there is flow to the backwater from the main stream. At high river stages, the depth increases and the effect of the towboats for resuspension of sediments decreases as indicated in the previous discussion. The natural level of turbidity is greater because of the fine sediments carried by the inflows to the rivers from adjacent (farm) lands. Comparative turbidity levels behind towboats at normal and high river stages are illustrated in Figure 13. The background level of turbidity is higher, at high river stages, and although the towboat increases the turbidity, its effect is smaller than at low river stages due to increased depths as discussed in Section 3.2.

4.0 BOAT-GENERATED WAVES AND THEIR EFFECT ON THE RIVER SYSTEM

4.1 General Wave Description

The basic wave forms that are generated by boats were shown in Figure 1. Normally, a moving surface vessel developes a set of waves at both its bow and stern. A series of diverging waves are also propagated from each side of the boat in an oblique direction away from the vessel and a series of transverse waves are created that propagate in the same direction as the boat. As the waves propagate away from the boat, the amplitude of the divergent waves decrease slowly, thus even at a large distance (relative to channel width) from the boat, wave amplitudes are significant.

Waves generated by boats represent a transfer of energy from the boat across the water to the shore. The energy contained per unit of wave surface is directly proportional to the square of the wave height. Thus, wave height is of principal interest in considering the effects of the waves on river banks.

Waves are generally classified as deep, intermediate and shallow. Deep water waves occur when the depth of water is greater than approximately

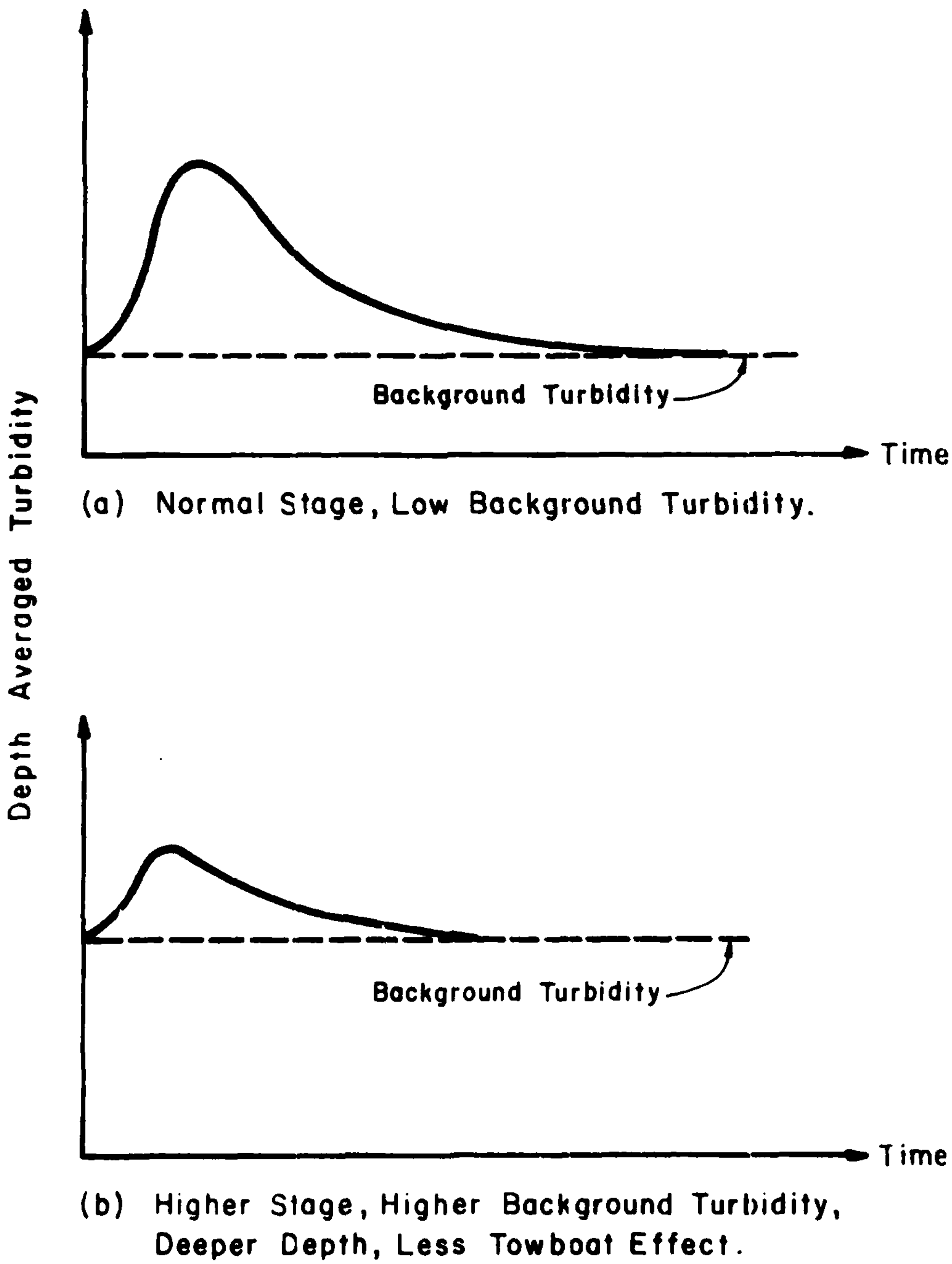


Figure 15. Towboat Effects on Turbidity with River Stages.

half the wave length, and shallow waves occur when depth is less than approximately 1/20 of the wave length. Deep water waves have a celerity (speed of wave propagation) independent of depth whereas the speed of propagation of shallow waves are dependent on depth.

The heights of waves generated by a boat are almost entirely dependent on boat speed. Large towboats which move at relatively slow speeds generate smaller-height waves than small pleasure crafts moving at higher speeds, (Sorenson, 1967, Bidde, 1968). The stern waves are more prominent than bow waves. A trough precedes the stern wave of towboats, and both the trough and crest of the stern wave propagate to the banks. The difference in wave patterns generated by a small pleasure craft and a large towboat can be seen in the infrared photographs of Figures 14 and 15. Wave heights generated by the small boat moving at high speed are clearly seen to be greater than wave heights generated by a large towboat moving at a slower speed.

Near the banks, waves undergo transformations resulting in increase of height as water depth decreases. The wave speed also reduces with decrease in depth which causes refraction of the waves near the shore or bank line. Waves breaking near the bank and refraction of the waves can be seen in Figure 14b.

4.2 Wind Waves

Portions of the river system such as pools and lakes are particularly susceptible to wind waves. In these reaches, wind waves are more persistent than waves generated by boats, and have greater effect on the banks. Wind waves in comparison to waves generated by a towboat can be seen in Figure 15. In wave heights, the wind waves could be comparable to waves generated by boats, dependent on wind

Direction of Flow

a. Mississippi River near LaCrosse, Wisconsin.

Direction of Flow

b. Illinois River near LaSalle Illinois.

Figure 14. Waves from Small Fast Pleasure Boats.

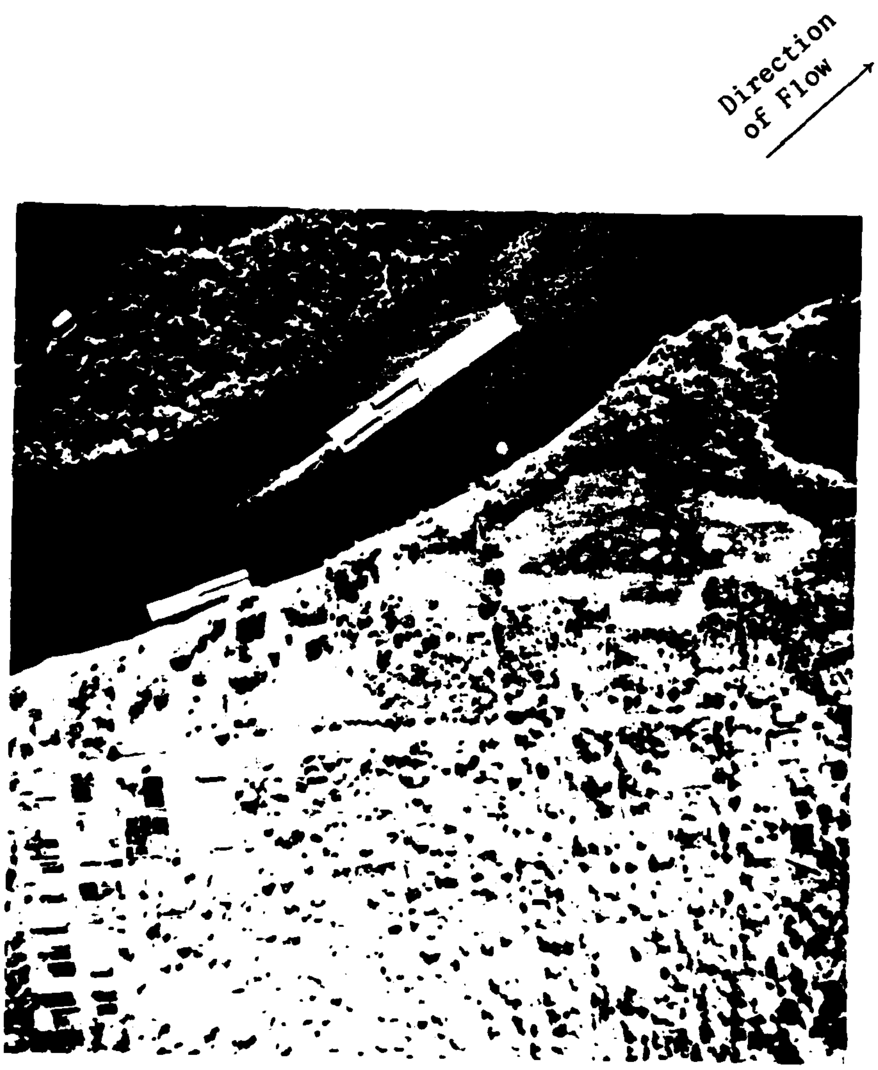


Figure 15. Waves from Towboat and Wind Waves.

speed, duration and fetch. In narrow channels, wind waves are smaller than boat waves because of limited fetch.

4.3 Wave Effects on River Banks

Near the river bank, the decrease of water depth decreases wave celerity; steepens the wave crests until the waves eventually break. When waves break, kinetic energy is partly converted into turbulence, and turbulence in turn suspends fine material along the shore line. The effect of waves generated by a fast moving small craft can be seen in Figure 14b, along the left bank (looking downstream). If waves do not break, the wave runs up the shore, or impacts against the bank and if the bank is unstable, can cause erosion. The alternate motion of runup and backwash of the waves on the shore can also cause erosion. On a gentle sloping shoreline an equilibrium slope is eventually achieved. Steep, or near vertical, river banks will be continually attacked by waves, and if the bank material is erodible or unstable, bank failure can be expected.

The effects at the river bank of waves from towboats are different from wave effects of small boats. The bow wave height from towboats is small, and there is a long shallow trough between the bow wave and the stern wave which is manifested at the river bank as a drawdown of the water surface. Depending upon the distance of the towboat from the bank, the lateral waves, which are transverse to the sailing line and moves with the speed of the towboat, either lags the diverging stern wave, is coincident with the stern wave or precedes it. Because the lateral waves also transform in wave height, the appearance is different at the bank in shallow water than farther out in the river. The first lateral wave encountered at a stationary point on the bank appears as a surge moving into the drawdown region. If the river bank is steep, and the water is therefore deep at the banks, the lateral waves do not break and an observer at a point on the bank would see a series of low amplitude waves following passage of a towboat.

4.4 Effects of Increased Traffic on River Banks

There will be increase in wave activity with increase in river traffic. The effects of increase in waves on river banks will depend on bank stability, and river bank form. Most sections of the river system have had wave wash from winds and boats for many years and are quite stable. Additional waves of the same heights generated by increased river traffic are not likely to cause any significant increased rates of bank erosion where none is presently evident. Also, any river bank area that is being eroded by waves will continue to be affected, at an accelerated rate. For example, the predominantly cohesive silt-clay banks of the Illinois River have maintained essentially their same alignment throughout the past several decades of towboat activity whereas the less cohesive banks of the Mississippi River have experienced somewhat greater rates of erosion. The effects of waves from fast moving boats are more destructive to river banks than waves from slower moving towboats.

5.0 SUMMARY AND CONCLUSIONS

5.1 Sediment Resuspension

The resuspension of river bed sediments due to the passage of a boat is dependent on boat size, speed, draft, depth of channel, and size of bed material. Large towboats cause greater resuspension of sediments in the channel than smaller pleasure crafts due to their size and proximity to the river bed. The Illinois River is more susceptible to these effects than the Upper Mississippi River because of the finer bed material and generally shallower depths. Increasing river traffic will increase resuspension and thus turbidity at a rate proportional to the frequency of towboat passage. A three-fold increase in traffic will not increase turbidity three times that over the base comparative rate, however, a somewhat higher level of turbidity than which presently exists will be maintained due to the increased turbulence added by the boats.

If there is no spilling flow from the main channel to the backwater areas such as during low stages, the increased turbidity will be confined to the main channel. During high river stages when there is transport of turbid water from the main channel to backwater areas, the resuspended sediments will be carried with the flow and settle in the calmer water.

5.2 Wave Effects

Waves on the river may be generated by boats and wind. Boat-generated waves have heights primarily dependent on boat speed, thus wave heights from small pleasure crafts are larger than wave heights from large slow towboats. In wide channels, pools and lakes, wind waves may be more significant than boat waves. Effects of the waves on river banks from increased traffic would be to cause some resuspension of fine material along the shoreline and accelerate erosion on existing unstable banks.

5.3 Summary Example

The effects of both a towboat and pleasure boat on the lower Illinois River are illustrated in Figure 16. The trail of sediment resuspended by the towboat is evident for a long distance behind the boat. The small craft does not create a significant sediment plume. The waves generated by the towboat are smaller in height than the waves created by the following pleasure boat. The larger waves created by the smaller craft break on the shoreline. The wave effects at the bank which can be created by towboats, but which are not visible in the photograph of Figure 16, are manifested in a gradual rise and accompanying shallow trough followed by a surge near the bank.

6.0 ACKNOWLEDGMENTS

The authors wish to acknowledge the assistance of the U. S. Army Engineer District, St. Louis, Corps of Engineers and especially Mr. Gene Degenhardt, in obtaining color infrared aerial photographs to augment those taken by the authors as well as other general information such as maps of the river systems. Discussions with Dr. R. Sparks, of the Illinois Natural History Survey, is appreciated and his comments on the Illinois River were most helpful. We also wish to acknowledge our colleagues at Colorado State University, Drs. M. A. Stevens and D. B. Simons for their comments and suggestions relevant to this report.

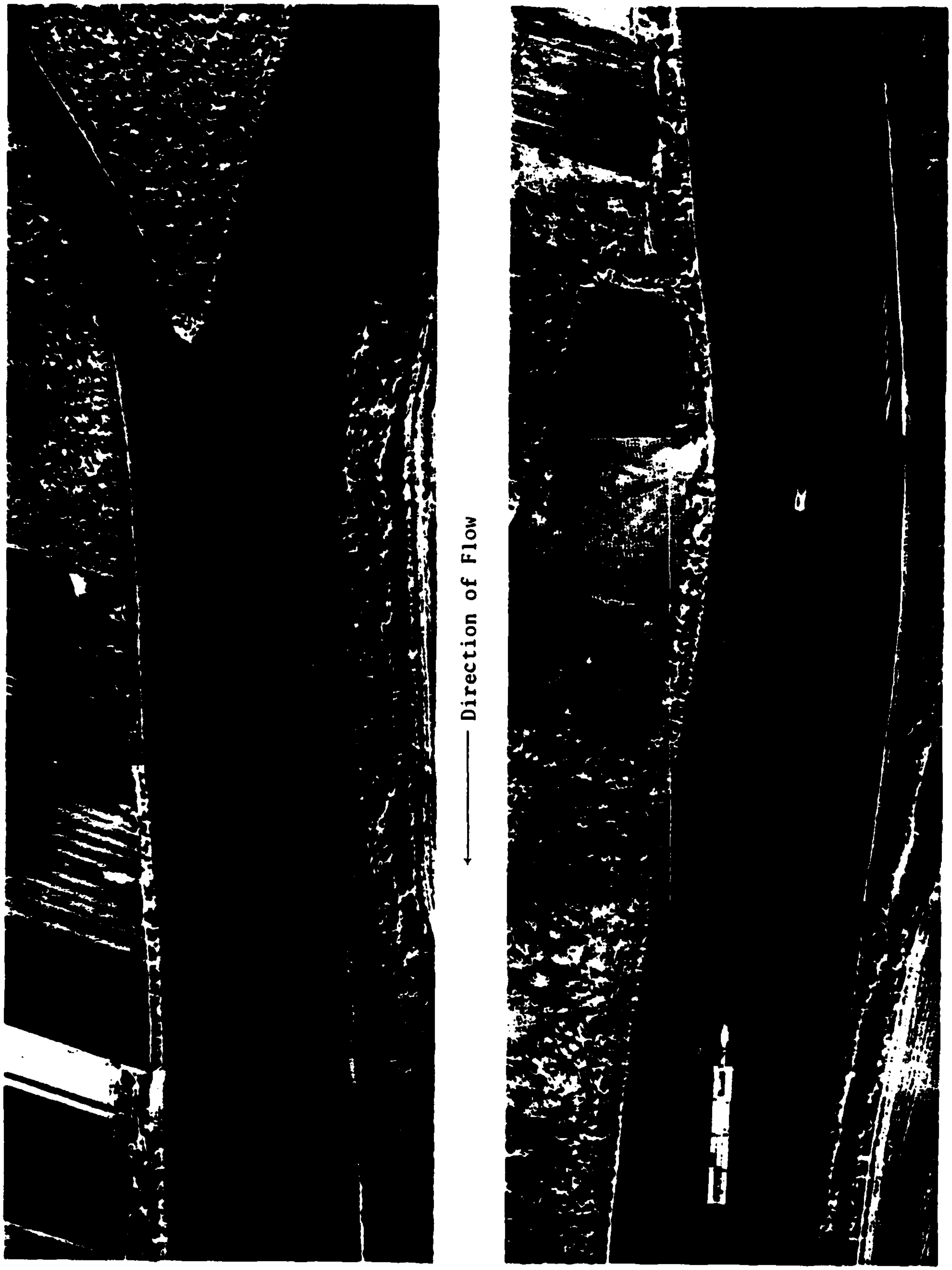


Figure 16. Summary Photograph of Towboat and Small Craft Effects on the Illinois River, near Hardin, Missouri. (Average Depth along Sailing Line is 16 feet).

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